

Concluding remarks on QCD-N'02 Workshop in Ferrara

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A summary is given of some important developments in QCD studies of the nucleon as presented at this workshop. Based on these developments some expectations for the short- and long-term future of the field are sketched. Taken together, the summary of the workshop and the future perspectives result in a *Road Map* for experimental studies of the QCD structure of the nucleon. The Road Map includes as a long-term goal the construction of new lepton-hadron scattering facilities both in Europe and the United States.

1. INTRODUCTION

The workshop on *The QCD Structure of the Nucleon* in Ferrara was organized in order to address the status and the future of the field, with the aim of arriving at a *Road Map* describing where and how to go in the next decade. The goal of the conference was ambitious, but well motivated. In recent years studies of QCD aspects of nucleon structure are faced with a number of striking developments, which are holding promise for the future:

- The renewed interest in sofar unmeasured distribution and fragmentation functions, in particular the transversity distribution $h_1(x)$, which enable us to obtain experimental information on new aspects of nucleon structure such as the tensor charge of the nucleon.
- The introduction of Generalized Parton Distributions (GPDs), which contain information on dynamic correlations between partons in the nucleon. The GPDs provide a unified framework that can be used for the description of a wide range of observables, and which encompass the well-known structure functions and nucleon form factors as limiting cases. This framework can also be used to demonstrate how deeply virtual Compton scattering (DVCS) enables us to determine the total angular momentum (J) carried by the partonic constituents of the nucleon.
- First observations of single-spin asymmetries in deep inelastic lepton scattering, demonstrating that – at least in principle – both the transversity distribution and the generalized parton distributions can be accessed experimentally.

While these developments issue new avenues in our field, some older subjects are going through a phase of rapid changes as well. Examples of such developments include lattice gauge theory, which is now being able to make a closer link to experimental observables, and the observation of new evidence in favour of Colour Transparency, a long-standing QCD-based prediction.

In these concluding remarks I will summarize these developments using the material presented at the workshop. This is the subject of section 2. In section 3 some – more subjective – impressions are given on the prospects of our field in the future. Which issues will most likely be resolved, and where should be the emphasis of our research efforts? The first preliminary data on the new observables mentioned above imply that new lepton-scattering facilities of high luminosity are needed in order to be able to carry out measurements of reasonable precision. A road-map that might lead to the realization of such facilities is sketched in the concluding section of this paper.

2. SUMMARY OF THE WORKSHOP

In the opening talk of the workshop P. Hoyer [1] described the fundamental problem addressed in our field as *”finding the structure of relativistic QCD bound states in a gluon condensate with spontaneously broken chiral symmetry”*. The importance of this problem was illustrated by mentioning that 98% of the mass of the proton originates from QCD binding effects, while only 2% is due to the Higgs mechanism. Hoyer asked whether a solution of this problem was within reach, and in answering this question he listed most of the aforementioned subjects using them as a sign for a promising future. These subjects are summarized below in separate subsections.

It is noted that necessarily only a subset of all material presented at the workshop is represented, and for illustrative figures the reader is referred to the original papers which are also contained in this volume.

2.1. The transversity distribution

Apart from the structure functions $F_{1,2}(x)$ and $g_{1,2}(x)$, there is a third leading-twist structure function $h_1(x)$ that is known as the transversity distribution. It is of great interest to measure $h_1(x)$, for which no data exist, since the transverse spin structure of the nucleon is expected to be considerably different from the longitudinal spin structure. Both chiral-soliton (instanton) models [3] and lattice gauge calculations [2] predict that the tensor charge $\delta\Sigma_q$ is considerably larger than the longitudinal quark spin contribution $\Delta\Sigma_q$. This is caused by the absence of gluon-splitting in the transverse case which results in a predicted relatively weak Q^2 dependence of $h_1(x)$.

Inclusive deep-inelastic scattering cannot be used to measure $h_1(x)$ as it is a chirally-odd quantity. In semi-inclusive DIS information on $h_1(x)$ can be obtained because it appears in the cross section expression in combination with a chirally-odd fragmentation function [4]. First evidence of a non-zero transversity distribution has been reported by HERMES [5]. In this experiment the single target-spin asymmetry for leptonproduction of pions was measured on a longitudinally polarized hydrogen target. The data show a small semi-inclusive asymmetry. It can be explained from the small transverse polarization component of the virtual photon combined with reasonable non-zero values for $h_1(x)$ and the corresponding chirally-odd fragmentation function (Collins effect [6]).

During the workshop an interesting discussion emerged concerning the interpretation of the single-spin asymmetries observed by HERMES. It was argued by Hwang [7] that the data could also be explained by the Sivers effect [8], i.e. a final state interaction between the spectator system and the current quark jet. The data reported by the E704 $p^\uparrow p \rightarrow \pi X$ experiment show a similar ambiguity. Moreover, as was stressed by Jaffe [9] the size of the asymmetries observed by HERMES and E704 is somewhat large for the (QCD based) expectation of a twist-3 effect. Makins [10] pointed out that future measurements on a transversely polarized target will be able to distinguish between the Sivers and Collins effects, as they give rise to a transverse single-spin asymmetry A_{UT} of opposite sign for either process.

Further complications in this emerging field of transversity studies may come from the Sudakov suppression of the Collins effect [11]. However, this effect is expected to be small at the relatively low Q^2 values exploited by the HERMES experiment. Moreover, Boer [11] showed that the introduction of weighting factors (proportional to $|p_\perp^\pi|/m_\pi$ with p_\perp^π the transverse momentum and m_π the mass of the produced pion) could remove this sensitivity to the Sudakov suppression.

The promise of future transversity studies was probably best illustrated by two projects for the 'aggressive theorist' as proposed by Jaffe [9]: (i) whether a relation exists between the difference of the transverse and longitudinal spin distribution functions and the orbital angular momentum; and (ii) whether the tensor charges (which can be derived from the transversity distribution) is somehow related to chiral symmetry breaking. These projects and the lively discussions on transversity during the workshop illustrate the growing importance of this field. However, what is needed first are high quality data and systematic comparisons of data collected in different experiments in order to establish that the canonical framework of hard QCD can be used when exploiting the new concept of transversity.

2.2. Generalized parton distributions

Generalized parton distributions (GPDs) are universal non-perturbative objects entering the description of hard exclusive electroproduction processes, such as $e + p \rightarrow e + p + \gamma, \rho, \omega, \pi$, etc. In the last few years, significant theoretical advances were made that allow to factorize the amplitude for such processes into a hard scattering diagram at the parton level, on the one hand, and the GPDs on the other. The internal quark-gluon structure of hadrons is encoded in these distributions.

There are four different GPDs: H , E , \tilde{H} and \tilde{E} . Each of them depends on the same three variables: x , the average of the longitudinal momentum fractions of the struck parton in its initial and final state, a skewness parameter ξ which measures the difference between these two momentum fractions, and t the momentum transfer to the target nucleon.

Generalized parton distributions (GPDs) encompass both the well-known parton distribution functions (PDFs) and the nucleon form factors as limiting cases. While the PDFs describe the probability to find a parton with fractional momentum x in the nucleon (forward scattering), the GPDs describe the interference or correlation between two quarks with momentum fractions $x + \xi$ and $x - \xi$ in the nucleon (off-forward scattering). Hence, the GPDs are sensitive to partonic correlations.

The subject of GPDs was nicely introduced at the workshop in the opening talk of

Hoyer [1], and further explained by Radyushkin [12], Mueller [13] and Burkhardt [14]. A number of interesting observations were made, of which I mention some of the most important ones:

- GPDs unify existing ways of describing hadronic structure, and allow for accessing new information on partonic correlations.
- GPDs allow the simultaneous determination of the longitudinal momentum and transverse position of partons (*"hadron tomography"*).
- GPDs are sensitive to chiral symmetry breaking effects.
- Educated guesses of GPDs result in predictions of cross sections and single-spin asymmetries that are surprisingly close to the data.

One can summarize these observations by noting that the GPDs present a new powerful interface between fundamental calculations of hadronic structure (such as lattice QCD and chiral-soliton models) and many different kinds of observables.

Many of these ideas were translated into practical calculations by Vanderhaeghen [15], who stressed the importance of measurements of GPDs in the domain $-\xi < x < \xi$, where the sensitivity to $q\bar{q}$ -correlations is particularly strong. As an example he showed a calculation of the beam charge asymmetry A_{ch} for deeply virtual Compton scattering (DVCS), where the size and shape of the $\cos(\phi)$ dependence of A_{ch} is entirely driven by these $q\bar{q}$ -correlations, which are usually referred to as the 'D-term'. Ellinghaus [16] presented first low-statistics data on A_{ch} obtained at HERMES that are well described by these calculations.

The experimental investigation of DVCS represents just one avenue in obtaining information on the GPDs. Guidal [17] described how systematic measurements of cross sections and asymmetries in DVCS, and longitudinal meson electroproduction will enable us to obtain separate data on the four known GPDs. He also introduced two new classes of deeply virtual Compton scattering experiments:

- Double DVCS (DDVCS) in which a virtual instead of a real photon is produced in the final state. This process would make it possible to study the x and ξ dependence of the GPDs separately, but has the disadvantage that very high luminosities are required.
- DVCS with a Δ resonance in the final state (Δ VCS), which can be identified by observing the Δ decay products simultaneously with the produced photon. This process would make it possible to estimate the Δ contribution to DVCS, which is especially useful for experiments lacking sufficient resolution to separate the Δ from the nucleon ground state.

Examples of first measurements that revealed the potential of the GPD framework were presented by Hasch [18], Elouadriri [19] and Favart [20]. Although the data are still of modest quality, it is striking that all cross sections and asymmetries measured (by ZEUS, H1, HERMES and CLAS) are well reproduced by the available calculations. However, it will require enormous improvements in experimental capabilities (both in terms of

energy resolution, and in particular luminosity) before it will be possible to determine the x , ξ and t dependence of the four GPDs from the data. Moreover, as the observables correspond to integrals over (a sum of) GPDs, the extraction of H , E , \tilde{H} and \tilde{E} will always involve some model dependence. Korotkov [21], however, showed that under reasonable assumptions the remaining model dependence is weak if $H(\xi, \xi, t)$ is extracted from DVCS measurements of single beam-spin asymmetries for small t .

Apart from their intrinsic interest (as probes of $q\bar{q}$ -correlations), the determination of GPDs is needed to map out the angular momentum structure of the nucleon. In 1997 Ji [22] has shown that the first moment of H and E equals twice the total angular momentum carried by the quarks and gluons – in the limit $t \rightarrow 0$. By comparing the total angular momentum to the spin content of the nucleon as measured in polarized deep-inelastic scattering experiments, one gets access to the (gauge dependent) orbital angular momentum of the partons.

This finding triggered the enormous interest in the experimental study of DVCS described above. I refer to the talks quoted above for a more detailed account of these new data [16,18–20]. However, it was pointed out by Vanderhaeghen [15] that transverse spin asymmetries observed in longitudinal vector meson production also reveal a surprising sensitivity to the total angular momentum carried by the quarks. Within their chiral soliton model calculations, they showed changes of the asymmetry from -0.15 to -0.30 if J_u was changed from 0.1 to 0.4. It remains to be seen to what extent such measurements are feasible in view of the required identification of the longitudinal component of the reaction, $\gamma_L^* + p \rightarrow \rho_L^0 + p$, and in view of possible model dependences.

2.3. QCD effects in nuclear matter

In her presentation on diffraction in ep -scattering, Abramovich [23] referred to two aspects of vector meson production which can be seen as a link between the subjects discussed in the previous and present subsections:

- Calculations for new ZEUS and H1 data on diffractive Υ production at $W \approx 140$ GeV are shown to be highly sensitive to the chosen GPD parameterization (up to a factor 2). Unfortunately, the data are not yet sufficiently precise to distinguish between the various calculations, but the example shows the large range of applicability of the GPD framework.
- When describing diffraction in terms of the interaction between a $q\bar{q}$ -pair (originating from the hadronic structure of the virtual photon) and the target, it is assumed that the $q\bar{q}$ -pair has a small transverse size. As a result of its small size the $q\bar{q}$ -pair is assumed to represent a (white) color dipole, which interacts only weakly with the proton. In other words Colour Transparency is assumed to be valid.

While Abramovich assumed the validity of Colour Transparency (CT), this striking QCD prediction still has not been definitively demonstrated to exist by experimental data. This became evident in the talk of Strikman [24], who reviewed the present experimental evidence supporting this QCD prediction: (i) the observed A-dependence of 2-jet production in pion induced experiments (E-791) at $E_\pi = 500$ GeV ($A^{1.61 \pm 0.08}$) is in agreement with the CT-based prediction ($A^{1.54}$); and (ii) the slope of the t -dependence of vector meson production shows the expected reduction with Q^2 , albeit with poor statistics. At

the workshop Borissov [25] presented new additional evidence in favour of colour transparency based on the analysis of coherent ρ^0 production on ^{14}N collected at HERMES. By studying the Q^2 -dependence of the nuclear transparency in ρ^0 production while keeping the coherence length constant, he found an increase with Q^2 of the transparency by $0.081 \pm 0.027 \text{ GeV}^{-2}$, which is consistent with the prediction based on colour-transparency of 0.07 GeV^{-2} . It is concluded that the experimental evidence for this QCD prediction is finally accumulating, after many false attempts in the past.

Another unverified QCD prediction discussed by Strikman [24] concerns the energy loss of partons propagating through nuclear matter. According to QCD the energy loss per unit distance dE/dL is proportional to the distance traversed, which is different from our intuition based on the Bethe-Bloch expression. In a recent paper Wang [26] used such a QCD approach to calculate the energy loss in hot and cold nuclear matter. These results were discussed by Muccifora [27], who presented semi-inclusive deep-inelastic scattering data collected by the HERMES collaboration on various unpolarized nuclear targets. By comparing the hadron yield per DIS event on nuclei to the same yield on deuterium, a significant (energy dependent) attenuation is observed. This hadron attenuation in ^{14}N and ^{84}Kr is well described by the aforementioned calculations of Wang if a value of $dE/dL \approx 0.3 \text{ GeV/fm}$ is taken. This value for the partonic energy loss in cold nuclear matter can be compared to the energy loss derived from recent PHENIX data [28] on π^0 production in Au+Au collisions at $\sqrt{s} = 130 \text{ GeV}$, yielding 0.25 GeV/fm [26]. If the PHENIX number is converted to the corresponding energy loss in the initial hot stage of the Au+Au collision, a value of about 5 GeV/fm is found. Comparing this number to the value derived from the HERMES data for cold nuclear matter, it was concluded by Muccifora [27] that the gluon density (which drives the energy loss) is a factor 15 higher in the initial phase of the Au+Au collision. This result reflects a new synergy between two fields that used to be essentially independent: relativistic heavy-ion collisions, and deep inelastic scattering.

2.4. Other recent developments

Many other subjects were discussed at the workshop, not all of which can be covered in this summary. On the experimental side, important reports on the status of the COMPASS experiment [29] at CERN and the RHIC experiments [30] at BNL were presented. The COMPASS experiment has carried out a successful commissioning run in late 2001, and real data taking is expected to start in 2002. At BNL an important break-through was reported, since it has been shown to be possible to inject and maintain two polarized proton beams in RHIC at $\sqrt{s} = 100 \text{ GeV}$. These technical developments imply that many more high-quality data are to be expected in the nearby future.

On the theoretical side, very important developments in the field of lattice gauge calculations were reported. Negele [31] and Rakow [32] described these results, which I summarize below:

- The improved computing capabilities enable lattice QCD calculations at smaller lattice spacing (a), large lattice volumes (L^3) and -most importantly- smaller pion masses (m_π).
- The differences between quenched (no sea quarks) and unquenched calculations turn

out to be minimal.

- In order to make much more realistic extrapolations to light pion (or quark) masses Chiral Perturbation Theory is successfully invoked.

Although many improvements are still needed, it is gratifying to see that lattice QCD now is able to reproduce many experimental observables such as moments of parton distributions.

3. FUTURE PERSPECTIVES

The developments described in the previous section imply that the study of the QCD structure of the nucleon is entering a new phase. Many new high-precision data will become available in the nearby future from HERMES, JLab, COMPASS and RHIC-spin. At the same time the framework of generalized parton distributions has extended dramatically the number of well-defined observables that can be used to compare experimental results with theoretical calculations such as those based on the chiral-soliton (or instanton) models or advanced lattice QCD calculations. This atmosphere of progress and anticipation was clearly present at the workshop.

More specifically the following experimental results can be expected in the next 5 years (or so):

- *Flavour decomposition of nucleon spin:* Precise spin-dependent distribution functions for separate flavours, i.e. $\Delta u(x)$, $\Delta d(x)$, $\Delta \bar{u}(x)$, $\Delta \bar{d}(x)$, and $\Delta s(x)$ will be produced by HERMES, COMPASS and RHIC spin.
- *Gluon Polarization:* following the pioneering measurements at HERMES [33] considerably more precise data on $\Delta G/G$ are expected from COMPASS, SLAC experiment E161 and RHIC spin.
- *Transversity:* measurements with transversely polarized targets are scheduled at HERMES in the next couple of years, and will soon be followed by similar measurements at COMPASS and (somewhat later) at RHIC. Hence, first (but by no means complete) measurements of the u -quark transversity distribution $\delta u(x)$ will be available.
- *Generalized Parton Distributions:* measurements of deeply virtual Compton scattering and exclusive (vector) meson production will be continued at JLab and HERMES. Many reaction channels will be explored, but the kinematic ranges and luminosities available will severely limit the extraction of the complete x , ξ and t dependence of the GPDs.
- *Search for missing resonances and hybrids:* although not covered at the workshop, the search for new baryon resonances and hybrids also constitutes an important avenue in studying the QCD structure of nucleons and baryons. At present, and in the nearby future, these searches are being conducted at JLab (CLAS), ELSA, GRAAL and SPRING8, for instance. These facilities (soon supplemented by MAMI-C) will provide good data in the non-charm sector.

Hence, a wealth of data is to be expected in the coming years. If these data are accompanied by similar theoretical efforts, considerable progress can already be expected at a time scale of 5 to 7 years.

4. A ROAD MAP

Although many results are expected in the next 5 years, it is also clear today that many questions will remain unanswered. As an example the study of generalized parton distributions can be mentioned, which will require new electron-scattering facilities of high luminosity. Similarly, the determination of the tensor charge of the nucleon through the measurement of the transversity distribution will also require high precision measurements, which cannot be carried out at existing facilities.

With these arguments in mind, the end of the workshop was devoted to presentations and a subsequent discussion on future facilities. Rather than summarizing the physics objectives of each of these facilities, which one can find in the preceding papers, I decided to focus on answering the key question for which the workshop was organized, i.e. where and how to go in the next decade? It was the aim of this workshop to arrive at a *Road Map* of the type that can be found in OECD reports describing future plans in high-energy physics, for instance [34].

Following the example of Ref. [34] I sketched the following road map, admitting that some of the choices carry a personal bias:

1. Exploit current frontier facilities in our field such as COMPASS, HERMES-II, JLab and RHIC-spin, until surpassed by new facilities.
2. Form a coherent long-range plan shared by the entire community in our field. This is of particular importance in Europe, where no such tradition exists.
3. Prepare for the approval and construction (*before 2008*):
 - The JLab 12 GeV upgrade [35] including the equipment for the proposed new real photon experiments (Hall D)¹.
4. Establish a vigorous R&D program to fully develop (*for exploitation after 2008*):
 - A fixed target eN machine in Europe with polarized beams and targets [38], $E_e = 25 \div 100$ GeV, and a luminosity of about 10^{35} N/cm²/s.
 - The electron-ion collider (EIC) at BNL [39] with both beams polarized, $\sqrt{s} \approx 30 \div 100$ GeV, and a luminosity of about 10^{33} N/cm²/s.

The project mentioned for the mid-term future is an existing proposal, which has already been given to the funding agencies. The required investments are modest as compared to the budgets required for the projects listed under item 4, and the physics objectives concern the search for hybrids and missing resonances².

The most important and most challenging projects for studying the QCD structure of the nucleon are listed under item 4. Also in this case there is a nice complementarity

¹ In this respect one could also mention the European high-energy storage ring (HESR) project at GSI [36], which will provide $1.5 \div 15$ GeV/c (cooled) anti-proton beams impinging on fixed (internal) targets. This project was not discussed at the workshop, but has a similar scope as the JLab 12 GeV project.

² Actually, similar arguments apply to the HESR facility. However, while the JLab project concentrates on the uds -quark sector, the HESR project focusses on the charm sector.

between the EU- and US-plans: while EIC exploits the benefits of a collider experiment, the European plans have the advantage of a higher luminosity. Several scenarios already exist for a high-intensity eN -facility in Europe [37]. Moreover, at the workshop, a novel scenario was discussed by von Harrach [38], in which use was made of the existing infrastructure of the HERA ring at DESY. Although the accelerator configurations proposed in the various scenarios are different, the physics motivation is the same; the study of semi-inclusive reactions to determine the transversity distributions, and the study of exclusive reactions to access the Generalized Parton Distributions, requiring in both cases high-intensity (polarized) electron beams and polarized targets. For the semi-inclusive studies the optimal beam energy range is $50 \div 100$ GeV, while beam energies of $25 \div 50$ GeV are more suitable for extracting cross sections and their scale dependence in exclusive measurements. The new European initiative [41] discussed at the workshop aims at incorporating both objectives into one new proposal.

In the nearby future, item 2 of the *Road Map* given above is probably the most important one. Within Europe a unified view needs to be developed regarding future QCD studies of the nucleon. In this respect it is very fortunate that NuPECC has initiated the development of a new long range plan with one working group dedicated to the study of QCD [40]. As input to this working group it is of great significance that a large fraction of our community has expressed its support for the development of a high-intensity eN -facility in Europe by signing the *Declaration of Ferrara* [41]. For this initiative and the excellent organization of the workshop QCD-N'02 the organizers, and more in particular Wolf-Dieter Nowak and Enzo de Sanctis, deserve all praise.

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